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Code-Division Multiple-Access in an Optical Fiber LAN With Amplified Bus Topology: The SLIM Bus

D. A. Chapman, P. A. Davies, and J. Monk

Abstract—A novel optical fiber network with a bus topology and dark signaling (the SLIM bus) using optical code-division multiple-access (CDMA) is proposed. With a new design of delay line correlator the network is shown to eliminate optical beating noise and overcome the main limitations of incoherent optical CDMA in a star topology.

Index Terms—Code-division multiple-access, local area networks, optical fiber communication, optical fiber delay line filters.

I. INTRODUCTION

INTEREST in optical code-division multiple-access (CDMA) has been increasing over the past 20 years because the code generation and correlation can be done optically with optical fiber delay-lines [1]. This removes the need for high-speed (chipping rate) electronics and provides a means to exploit the vast potential bandwidth of fiber. Unfortunately it has more recently been shown [2] that in practice the effects of optical beating at receiver photodiodes seriously compromises the performance of fiber networks utilising multiple optical sources, and it has been suggested that this limits the relevance of optical CDMA to niche applications [3].

The network described here eliminates optical beating and, because it uses a single narrowband optical source, dispersion is reduced allowing long spans, it is potentially scalable with wavelength division multiplexing and it has none of the near-far effects that can significantly degrade the performance of CDMA [4].

A. Network Description

The network is a folded bus (Fig. 1) with a single continuous wave (CW) light source at one end. Signals are applied to the bus by in-line modulators [5] which generate “dark pulses:” we refer to this as dark signalling and use the acronym SLIM for *Single Light-source with In-line Modulation*. Power levels are maintained with optical amplifiers.

At the receivers, power is tapped from the bus and fed into a fiber delay-line optical correlator. Because of the dark signaling, an autocorrelation “peak” is ideally represented by zero optical power at the correlator output when there is a dark chip on each tap of the correlator. The receiver synchronizes to the originator’s data rate by locking a local clock to the (dark)

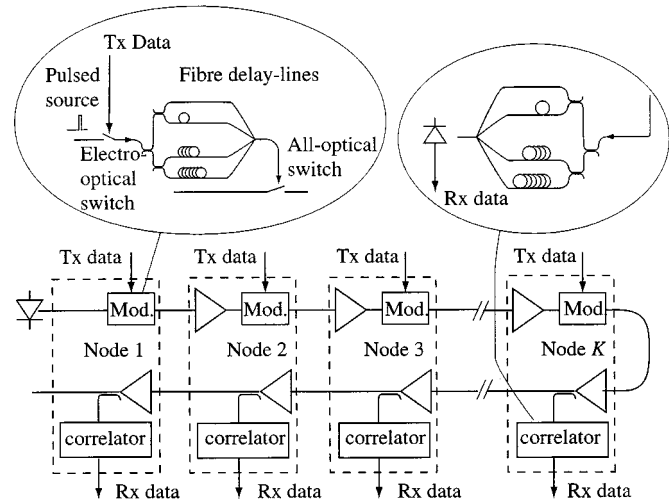


Fig. 1. The SLIM bus.

peak of the autocorrelation functions. Once synchronized, the receiver examines the chip period corresponding to the autocorrelation peak (the decision instant) in each bit interval, and uses threshold detection on the signal current to decide on the data value. As with other optical CDMA (OCDMA), the signal processing (both sequence generation and correlation) may be done optically using fiber delay lines, so that no electronics operates at the chipping rate. The in-line modulator must operate at the chipping rate, but using the configuration of Fig. 1 the modulator is an all-optical switch, for which terahertz technologies are emerging [6].

There is no optical beating between multiple optical sources in the SLIM network because there is only one shared source. However, there remains the potential for optical beating at the detector due to the multiple paths through the delay line correlator at the receiver. The extent of this beating and its effect on the error rate depends upon the design of correlator, and three variations on the correlator design will be considered.

The incoherent [7] and coherent correlators [8] are as previously proposed for OCDMA in star networks. Path length differences in the incoherent correlator are all much longer than the coherence length of the source, so when light is recombined it is as if there were multiple incoherent sources and beating is significant [9]. In the coherent correlator the path length differences are much shorter than the coherence length of the optical source and there should be no beating, but the optical source must be stable with a narrow linewidth, and the correlator must include phase and polarization control [8].

The third correlator design is a new proposal of this paper and referred to as a “hybrid correlator.” As with the other designs it splits light with a single-mode fused fiber coupler,

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D. A. Chapman and J. Monk are with the Department of Telematics, The Open University, Milton Keynes, MK7 6AA, U.K.

P. A. Davies is with the Department of Electronics, The University of Kent at Canterbury, Kent CT2 7NT, U.K.

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TABLE I
DEFAULT PARAMETERS FOR THE SIMULATION. SEE TEXT FOR CHANGES

Parameter	Value	Note
Laser launch power, P_L	1 dBm	
Fibre attenuation between nodes	3 dB	Includes any splice or connector losses
Modulator excess loss	3 dB	
Modulator extinction ratio, M	20	13 dB
Loss from bus to taps, γ	16 dB	Does not include splitting loss of $1/W$
Amplifier noise parameter, n_{sp}	2	
Photodiode responsivity, \mathcal{R}	1.25	
Photodiode load resistor	10000 Ω	
Electrical bandwidth, B_e	10^{10} Hz	Corresponds to signalling rate of 20 Gbit/s
ASE optical bandwidth, λ_N	25 nm	
Laser linewidth, λ_S	1 nm	Used only for the incoherent correlator
Number of nodes, K	49	
No. simultaneous users, N	8	
Code length, L_C	883 chips	(883, 6, 2, 1) Code from Yang and Fuja [15]
Code weight, W	6 chips	(883, 6, 2, 1) Code from Yang and Fuja [15]

but light is combined into a multimode fiber using a device similar to that reported by Yui *et al.* [10]. Intuitively it can be appreciated that if the light from each (single mode) tap couples into a different mode of the multimode output fiber then, because of the orthogonality of the modes, there will be no beating. In fact, provided the number of modes in the output fiber is equal to or greater than the number of input fibers, then in principle essentially all the light from the single mode fibers may be coupled into the multimode output fiber, independent of the phase and coherence of the light in the input fibers [9]. Although the light conveyed by any one of the modes of the output fiber may be noisy (due to beating between light originating in different input fibers), the sum of the power over all modes is free from beating noise. Provided there is no subsequent mode-selective loss there will be no noise due to optical beating at the photodiode output. (The hybrid correlator can be thought of as an extrapolation of the device proposed in [11] that uses orthogonal polarization modes in a birefringent fiber to eliminate optical beating in a two-path delay-line filter.) Since the output is from a multimode fiber the photodetector will need a larger area than for single mode correlators, which will limit the speed of operation of the receiver (which must respond within chip periods) due to the capacitance of the detector. However, metal–semiconductor–metal (MSM) photodetectors have recently been shown to combine large detection areas with high speed performance [12].

The hybrid correlator, therefore, makes no demands upon the coherence of the optical signal and requires no phase or polarization control, yet, like the coherent correlator, has no inherent insertion loss and introduces no optical beating.

II. SYSTEM MODEL

In the absence of noise, errors can result from multiple-access interference (MAI) by (dark) pulses from interfering users combining in such a way as to replicate the signature sequence of a user. The probability of error in the SLIM bus in this case is given by the same formulae as for OCDMA with conventional signaling in star networks in the absence of noise, and has been calculated by Azizoğlu *et al.* [13].

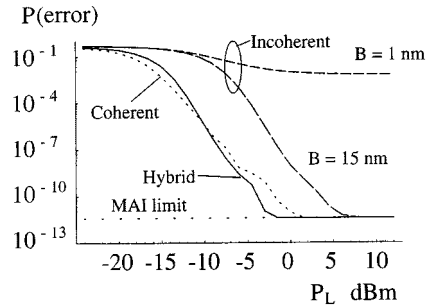


Fig. 2. Probability of error as a function of the power of the light source, for each of the three correlators.

When noise is included in the modeling it is necessary to consider all possible distributions of interfering chips and calculate the associated probability of error for each. Then

$$P_{\text{error}} = \sum_{\mathbf{k} \in \mathcal{K}} P(\text{error}|\mathbf{k})P(\mathbf{k})$$

where \mathbf{k} represents the distribution of interfering chips among the correlator taps at the decision instant, \mathcal{K} is the set of all possible \mathbf{k} and $P(\text{error}|\mathbf{k})$ is the conditional probability of error given the distribution \mathbf{k} . $P(\mathbf{k})$ is calculated from the number of simultaneous users and the code weights, and $P(\text{error}|\mathbf{k})$ depends upon many factors including optical signal and noise (amplified spontaneous emissions from the amplifiers) levels in the bus, optical beating at the photodetector, and thermal and shot noise in the receiver. The approach to the calculation draws on [13], taking into account the different optical beating for the three different correlators, and is described in [14]. In this letter we use the results of [14] to report on the predicted network performance, starting with the default parameters listed in Table I.

III. NUMERICAL SIMULATION RESULTS

Fig. 2 shows the probability of error (with the optimized decision threshold) as a function of laser source power. The high-power error floor for both the hybrid and coherent correlators is equal to the MAI alone, but the error floor for the incoherent correlator is much higher due to the optical beating. The effects of optical beating in the incoherent correlator can be decreased

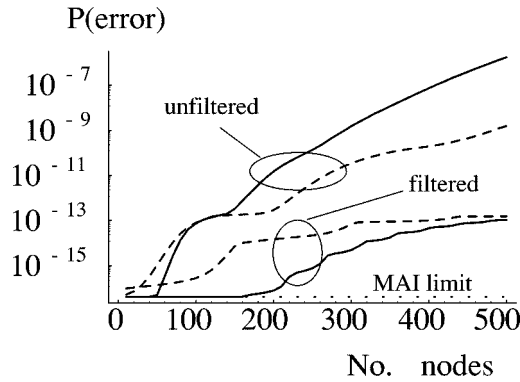


Fig. 3. Probability of error for ten simultaneous users as a function of the number of nodes. Dashed curves for coherent correlator, unbroken line for the hybrid correlator.

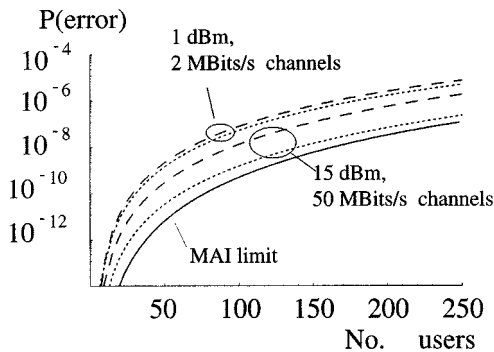


Fig. 4. Probability of error as a function of the number of simultaneous users on a 500-node network. Dashed line for coherent correlator, dotted line for hybrid correlator.

by increasing the optical bandwidth, and this effect is shown in Fig. 2 with the laser bandwidth increased to 15 nm. In this case the incoherent correlator can deliver MAI-limited performance, but requires a higher signal power due to the $1/W$ loss in the correlator.

Adding more nodes to the network increases the noise from the amplifiers' ASE. The consequences of this are demonstrated in Fig. 3, for ten simultaneous users. The codes of Table I would only allow 49 uniquely addressable nodes, so for Fig. 3 the code is changed to a 9001-chip code of weight-6 which, from [15] (using Construction 1), will allow an address space of 500. The ASE can be reduced by optical filtering at the receiver, and the effect of this is shown by the lower curves in Fig. 3. The minimum filter bandwidth is determined by the modulated laser linewidth, but so as not to make too severe demands upon the filter parameters (centre frequency and bandwidth) we make the conservative assumption of a 1-nm bandwidth.

Fig. 3 indicates that a 500 node network is possible, so Fig. 4 investigates the maximum number of simultaneous users that could be accommodated. With the parameters of Table I and the 9001-chip, weight-6, code, approximately 50 simultaneous users are possible for an error rate under 10^{-9} . However, the parameters of Table I are conservative in terms of the technology and from Fig. 2 we know that increasing the signal power allows MAI-limited performance to be approached with hybrid and coherent correlators. Optical processing at more

than 500 Gb/s has been reported in TDM experiments [16], so Fig. 4 also shows results from a simulation that assumes signalling at 500 Gbaud (giving a data rate per channel of more than 50 Mb/s), optical filtering (which has to be increased to accommodate the higher signalling rate) of 6 nm and an optical launch power of 15 dBm. With the optical power increased still further, above about 25 dBm, both the coherent and the hybrid correlators provide essentially MAI-limited performance. Notice the 'soft limit' characteristic of CDMA in Fig. 4, appearing as a slow rise in error probability as the number of simultaneous users increases so that, with the hybrid correlator and 15 dBm for example, 100 simultaneous users each operating at over 50 Mb/s result in an error probability of about 10^{-9} , but even with more than 250 users the error probability is below 10^{-6} . Such large numbers of simultaneous users are impossible with previously reported optical CDMA [3], because of optical beating.

IV. CONCLUSION

Optical CDMA using optical orthogonal codes is attractive for channel sharing because of the meritorious features of CDMA and because optical correlation bypasses the electronic bottleneck. The achievable performance of optical CDMA in star networks has previously been shown, however, to be seriously compromised by optical beating [3]. In this letter we have described an approach that virtually eliminates optical beating through the use of a single optical carrier in a SLIM bus combined with a new proposal for an optical correlator: the hybrid correlator.

We have shown that a 500-Gbaud SLIM network with 500 uniquely addressable nodes can have an error probability of about 10^{-9} with 100 simultaneous users and an error probability of less than 10^{-6} with 250 simultaneous users, each operating at more than 50 Mb/s. We have shown that the SLIM bus allows the potential of optical CDMA to be realized, but the efficiency of channel utilization of optical CDMA is inherently limited by multiple access interference and the SLIM bus could use other multiple access schemes if greater utilization is required. This is for further investigation.

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